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Challenges and solutions towards natural prefabricated vertical drains

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Abstract

In recent years, natural fibres such as jute and coir are emerging as a reasonable alternative to synthetic materials because they do not only have favourable engineering characteristics but also degrade biologically over time. Of promising applications of those environmentally friendly materials, natural prefabricated vertical drains (NPVDs) have received considerable attention, however their application is still limited. This paper summarises existing issues which are hampering these novel drains from a wider application, followed by studies carried out by the authors to overcome those limitations. Particularly this includes: (1) hydraulic properties of NPVDs considering macro and micro features; (2) modelling NPVDS including analytical method and a novel numerical approach to capture micro-hydraulic behavior of fibre drains considering fluid-fibre interaction; (3) bioderadable characteristics of NPVDs exposed to saturated soft soils; (4) analytical and numerical solutions to incorporate biodegradation of NPVDs into consolidation of soil.

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CHALLENGES AND SOLUTIONS TOWARDS NATURAL PREFABRICATED VERTICAL DRAINS

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ABSTRACT

In recent years, natural fibres such as jute and coir are emerging as a reasonable alternative to synthetic materials because they do not only have favourable engineering characteristics but also degrade biologically over time. Of promising applications of those environmentally friendly materials, natural prefabricated vertical drains (NPVDs) have received considerable attention, however their application is still limited. This paper summarises existing issues which are hampering these novel drains from a wider application, followed by studies carried out by the authors to overcome those limitations. Particularly this includes: (1) hydraulic properties of NPVDs considering macro and micro features; (2) modelling NPVDS including analytical method and a novel numerical approach to capture micro-hydraulic behavior of fibre drains considering fluid-fibre interaction; (3) bioderadable characteristics of NPVDs exposed to saturated soft soils; (4) analytical and numerical solutions to incorporate biodegradation of NPVDs into consolidation of soil.

1 INTRODUCTION

Over many years, synthetic materials have been used widely in geoengineering applications, which however has raised concern from environmental perspectives because of the high resistance of polymeric materials to biodegradation and, consequently, its long term negative effect on the natural environment (Gregory and Andrady, 2003). Natural fibres such as jute and coir are thus used as geomaterials in recent years, for example vertical drains (Lee et al., 1994; Kim and Cho, 2008), soil reinforcement (Lekha and Kavitha, 2006; Babu and Vasudevan, 2007) and filtration (Li et al., 2009; Vinod and Minu, 2010). These natural materials do not only have preferable engineering features but also degrade biologically over time. Furthermore, they can be found abundant in many developing countries where there is usually a high demand of soil treatments, so widening these naturally occurring materials in geoengineering would stand the society and economics of those regions in better stead.

Previous studies (Lee et al., 1994; Kim and Cho, 2008; Asha and Mandal, 2012) through experimental and field observations indicate that using natural fibres such as jute and coir to create natural prefabricated vertical drains (NPVDs) is a cost effective approach in comparison to conventional PVDs. However their application is still very limited although they have been introduced for almost 30 years (Lee et al., 1987). This is because of following reasons:

- *(i)* The major issue of NPVDs is their low efficiency in manufacture because of large labour costs, which means these drains are less economically comparative to synthetic PVDs which can be mass produced by polymers.
- *(ii)* Although NPVDs can have various options for material and structure but it is still under controversy of which can make the best manufacture productivity and discharge capacity. This results in a considerable confusion to manufacture and practice.
- *(iii)* There is a lack of studies which aim to provide an effective modelling approach to natural fibrous geomaterials. Most existing numerical methods are only able to model fluid flow through pre-formed porous media assuming unchanged porous characteristics while in fact there is a certain variation during fluid flowing due to fluid-particle interaction, resulting in an inaccuracy of the prediction.
- *(iv)* Natural fibres making NPVDs are inevitably biodegradable over time while limited studies address how it can happen in saturated soft soils. Previous studies (Lee et al., 1994; Jang et al., 2001) show a good performance of NPVDs without significant biodegradation during soil consolidating while other observations (Miura et al., 1995; Kim and Cho, 2009) in the field report a rapid degradation of jute drains. This unclarified issue has hampered this type of PVDs from a wider application.
- *(v)* The unique feature of NPVDs is their biodegradability however these drains can experience a rapid decomposition when they are exposed to adverse environments where cellulose degrading bacteria are available, which can deteriorate the drain's drainage capacity and result in a negative effect on the consolidation progress of soil. This requires a re-evaluation of conventional approaches which usually assume unchanged engineering characteristics of drains over soil consolidation.

This paper aims to present key findings from studies by the authors to clarify the above issues. In particular the following aspects are discussed in the paper:

a) A comprehensive investigation into the hydraulic properties of NPVDs made from jute and coir is carried out. This study clarifies whether NPVDs have a good discharge capacity in comparison to synthetic drains; and how mico-characteristics of fibres can affect the hydraulic conductivity of NPVDs. The outcomes help understand better the hydraulic behaviour of NPVDs, which plays a key role in solving issues (*i*) and (*ii*) above.

b) The paper also presents a novel numerical approach in which individual fibres are described by Discrete Element Method (DEM) while the fluid behaviour is captured by Computational Fluid Dynamics (CFD). This coupling method enables to simulate fluid flow through fibrous media while considering the fluid-solid interaction, which is a promising approach to overcome problem (*iii*) above. In addition, application of the analytical Kozeny-Carmen (KC) method to predict hydraulic conductivity of fibre drains is made and validated with the numerical and experimental data.

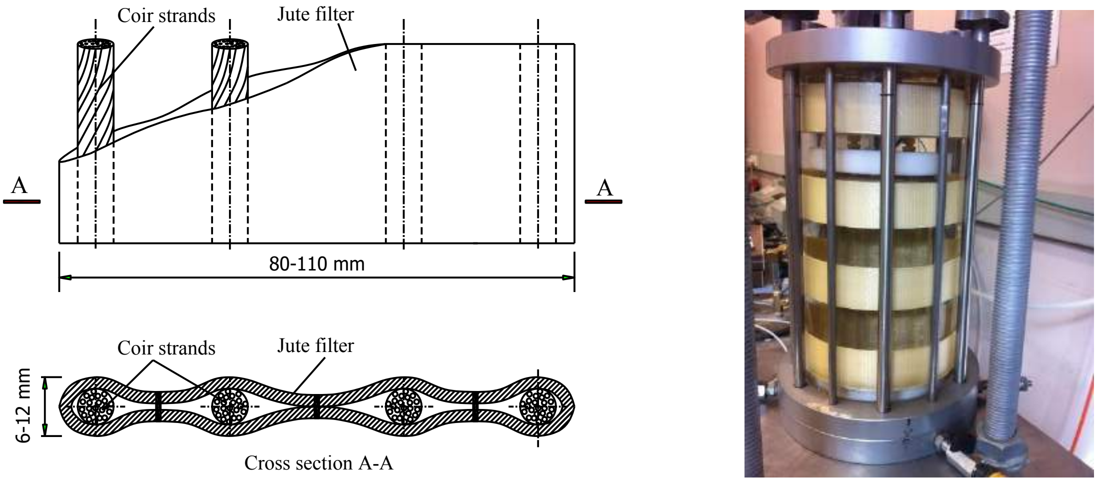
c) A laboratory study to investigate the biodegradation of jute drains buried in saturated soft soils is reported. Genomic (DNA) analysis to identify microorganisms in decayed fibres is carried out. This study is important to understand how cellulose based materials (e.g., jute and coir) can degrade biologically in saturated condition, which helps clarify issue (*iv*).

d) Analytical and numerical methods to predict soil consolidation with respect to the biodegradation of drains are proposed, which will address issue (v) above.

2 HYDRAULIC PROPERTIES OF NPVDs

2.1 DISCHARGE CAPACITY OF NPVDS (A MACRO-INVESTIGATION)

A series of discharge capacity tests were carried out on jute drains (a type of NPVDs) composed of jute filters and coconut cores (Figure 1a). The test model was established with reference to previous works (Jang et al., 2001) in which the drain was installed vertically in a cylindrical cell (Figure 1b). Different confining pressures were generated via cell pressure while the discharge volume of water at the outlet was recorded. The discharge capacity was calculated with respect to ASTM D4716 (2008).



a) Schematic of jute drains b) Drain being compressed in the cell

Figure 1: Discharge capacity test on jute drains

Figure 2 shows the discharge capacity of the drain used in the current study in comparison to previous studies including Jang et al., (2001) and Asha and Mandal (2012). The discharge capacity of the current drain is around 6.4x10^{-6} m^3/s at 10 kPa which is within the common range reported in previous investigations. The larger the confinging pressure, the lower the discharge capacity. For example the discharge capacity of jute drains in this study decreases to approximately 3.5x10^{-6} m^3/s at 100 kPa and becomes quite stable even though the confinging pressure continues to increase. This range of discharge capacity usually satisfies the requirement in practice, according to Chu et al., (2004) which suggest the required discharge capacity of PVDs from 0.5 to 4x10^{-6} m^3/s, depending on the drainage length and soil permeability. Note that different studies use different testing models and NPVDs, resulting in certain deviations in their discharge capacity.

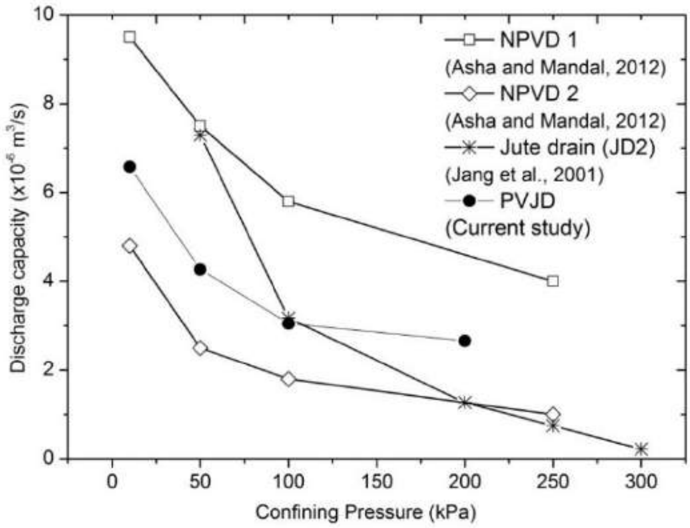
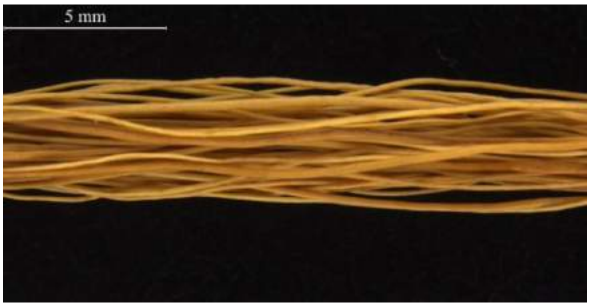


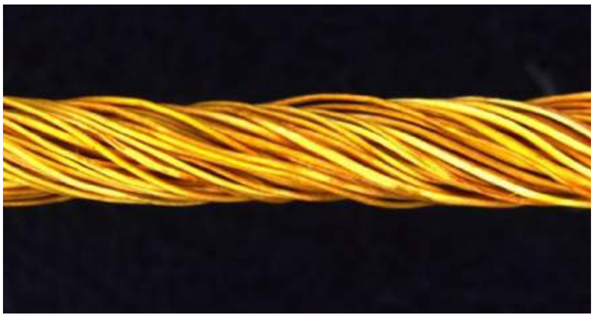
Figure 2: Discharge capacity of the current drain compared to other NPVDs

2.2 INFLUENCE OF MICRO-FEATURES ON THE HYDRAULIC BEHAVIOUR OF NPVDS

Most previous studies mainly focus on macro-hydraulic properties (i.e., discharge capacity) of fibre drains while the influence of micro-characteristics on the hydraulic behaviour of fibre drains has not been understood well. This section shows a laboratory investigation in which elemental fibre drains made from coir were subjected to a series of hydraulic tests. A pressure controlled model was adopted to determine hydraulic conductivity of drains. Two structures of fibre bundle, i.e., twisted and non-twisted fibres were created (Figure 3:). Different micro-characteristics including the size, shape, uniformity and the twisting angle of fibres were addressed. Fibre drains after hydraulic test were subjected to a post-analysis process including optical micro-imaging followed by image analyses to obtain porous features of the drains.



a) Non-twisted coir fibres

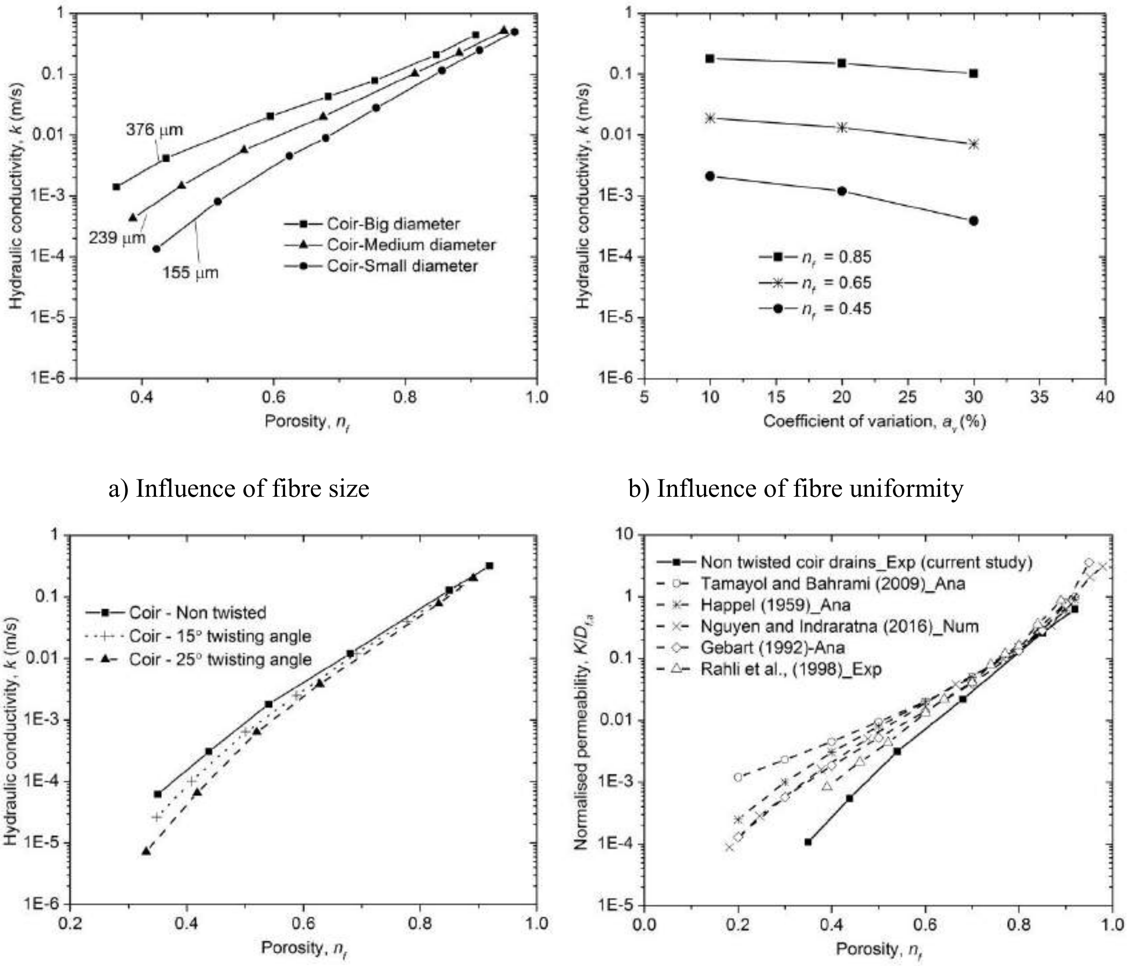


b) Twisted coir fibre drains

Figure 3: Experimental investigation into micro-hydraulic behaviour of fibre drains

Figure 4(a) shows that for the same level of porosity, the larger the fibre diameter, the greater the hydraulic conductivity of drains. Particularly for $n_f = 0.6$, the hydraulic conductivity of the drain was 3.1×10^{-3} m/s for the smallest fibre ($D_{f,a}$ = 155 μm) but it increases to 9.0×10^{-3} m/s and 21×10^{-3} m/s as $D_{f,a}$ rises to 239 and 376 μm, respectively.

The coefficient of variation σ_v which is defined as the ratio of the standard variation to the mean fibre diameter was used to present the size uniformity of fibres in a drain. Figure 4(b) shows that the more uniform fibres, the larger drain permeability. For example, when $n_f = 0.65$, k decreases from 3.0x10^{-2} m/s at σ_v = 10% to 1.7x10^{-2} m/s and 0.75x10^{-2} m/s at σ_v = 20% and 30%, respectively.



a) Influence of fibre size b) Influence of fibre uniformity

c) Influence of twisting angle d) In comparison to other studies

Figure 4: Influence of micro-characteristics on hydraulic behaviour of fibre drains (modified after Nguyen and Indraratna (2017b))

Figure 4(c) indicates a significant effect of twisting angle on the hydraulic conductivity of fibre drains. The larger the twisting angle, the smaller the hydraulic conductivity. For example, with $n_f = 0.5$ the non-twisted coir fibres result in a hydraulic conductivity of 8.5x10^{-4} m/s meanwhile the fibre drains being twisted by an angle of 15° and 25° have a lower hydraulic conductivity, i.e., 6.1x10^{-4} m/s and 4.8x10^{-4} m/s, respectively. This is because the more the fibres being twisted, the more complex and tortuous the fluid path.

In comparison to previous studies, the normalised permeability of coir drains agrees quite well as Figure 4d shows. Particularly for the porosity $n_f > 0.6$, there are insignificant deviations among different studies which use different methods including numerical, analytical and experimental approaches. However the deviations become more apparent as the porosity decreases. This is probably because different studies used different fibres having varying micro-characteristics, e.g., the diameter and shape of fibres, making considerable deviations in their hydraulic behaviour.

3 MODELLING HYDRAULIC BEHAVIOUR OF NPVDS

3.1 ANALYTICAL PREDICTION ON HYDRAULIC CONDUCTIVITY OF FIBRE DRAINS

Of the existing approaches to predict hydraulic properties of a porous medium, the analytical Kozeny-Carmen (KC) method is the most preferable in practice because of its simplicity in calculation. According to this solution, the permeability of a porous medium can be computed by:

$$K = \frac{1}{k_k A_o^2} \frac{n_f^3}{(1-n_f)^2} \tag{1}$$

where K is the permeability; n_f is the porosity; k_k is the so-called Kozeny constant; A_o is the specific surface of the medium.

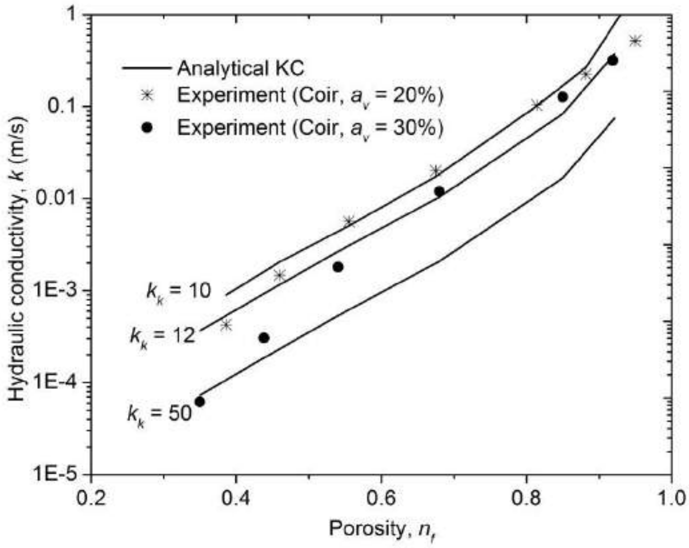


Figure 5: Validate KC method with experimental results of coir drains

Figure 5 shows the results from predicting hydraulic conductivity by KC method in comparison to the experimental data obtained in section 4 of this paper. The hydraulic conductivity predicted by KC method agrees with experimental data, particularly for the porosity $0.45 < n_f < 0.9$. The prediction is also influenced considerably by the uniformity of fibres. The larger the dispersion in fibre size, the less accurate the prediction. This is because the KC method is originally derived for homogeneous granular media. Note that the accuracy of KC method is also very sensitive to the empirical Kozeny constant k_k as Figure 5: shows.

3.2 NUMERICAL METHOD TO CAPTURE HYDRAULIC PROPERTIES OF FIBRE DRAINS

This section presents a numerical approach coupling fluid with particles to model hydraulic behaviour of fibre drains.

3.2.1 Theoretical background

Discrete Element Method (DEM) is employed to model individual fibres while Computational Fluid Dynamics (CFD) is used to describe fluid behaviour. The interaction between fluid and particles is managed by a mutual program.

Using DEM to simulate fibres means discretising a continuous thread into a number of individual elements which are then bonded together using a bond model. Fundamental governing equations of discrete elements are as follows:

$$m_i \frac{dU_{p,i}}{dt} = \sum_{j=1}^{n_i^c} F_{c,ij} + F_{f,i} + F_{g,i} \tag{2}$$

$$I_i \frac{d\omega_{p,i}}{dt} = \sum_{j=1}^{n_i^c} M_{c,ij} \tag{3}$$

Fluid behaviour is governed by the Navier-Stokes equations as follows:

$$\frac{\partial n_f}{\partial t} + \nabla.(n_f U_f) = 0 \tag{4}$$

$$\frac{\partial(\rho_f n_f U_f)}{\partial t} + \nabla.(\rho_f n_f U_f U_f) = -n_f \nabla p - f_p + \nabla.(n_f \tau) + n_f \rho_f g \tag{5}$$

where U_f, U_p are the velocity of fluid and particles, respectively; ρ_f is the density of fluid; p is the fluid pressure; m is the mass; F_c, F_f, and F_g are the contact, fluid interaction and gravitational forces, respectively. The mutual interaction between fluid and particles is considered through fluid-particle interaction forces. The total fluid-particle interaction force $\boldsymbol{F_f}$ presenting those fluid forces acting on particles might include the drag force, the pressure gradient force, the viscous force, and other unsteady forces (Zhu et al., 2007; Zhou et al., 2010). For soil improvement by vertical drains where laminar flow is predominant, unsteady forces are usually insignificant, so they can be ignored. Detail of these forces can be found in the studies by Nguyen and Indraratna (2016, 2017a).

How to bond distinct particles to generate fibres in DEM was discussed by Nguyen and Indraratna (2016, 2017a). Parallel bond models and its modified version proposed by Nguyen and Indraratna (2017a) which enables to simulate a nonlinear stress-strain relationship show a certain success in capturing tensile and bending behaviours of jute and coir fibres in DEM.

3.2.2 Results and discussion

Figure 6 presents the normalised permeability resulted from the CFD-DEM coupling applied for parallel fibres in comparison with other studies. The study shows a good agreement with previous numerical and analytical works particularly for medium and loose fibres, i.e., $n_f > 0.45$. When fibres become denser ($n_f < 0.45$), while the CFD-DEM coupling still agrees well with Happel (1959) and the analytical KC methods, it is considerably deviated from Tamayol and Bahrami (2008, 2009).

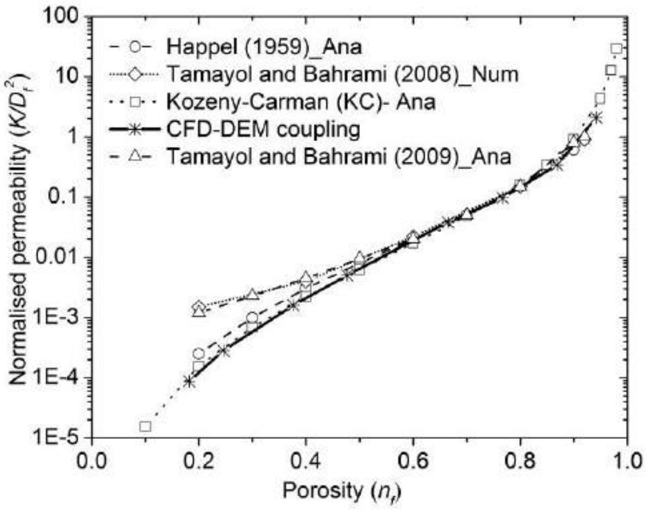
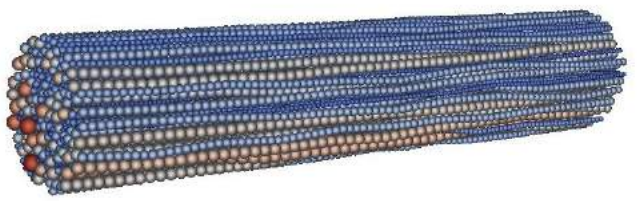
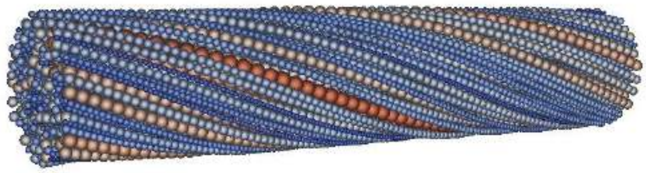


Figure 6: Permeability of fibrous media predicted by CFD-DEM coupling and other studies (modified after Nguyen and Indraratna (2016))

Micro-characteristics of fibre drains such as the diameter and position of fibres could be obtained through micro-observations and image analysis process. This information was then used to model fibre drains in DEM. Figure 7 shows how twisted and non-twisted fibres could be built in DEM. A fluid flow under different hydraulic gradient was created through these drains and the hydraulic conductivity was computed accordingly. Note that in this paper, only longitudinal flow is presented but the same concept can be used to model more complex flows such as transverse flow as shown by Nguyen et al., (2017)



a) Non-twisted fibre bundle



b) Twisted fibre bundle

Figure 7: Modelling non-twisted and twisted fibre drains in DEM

Figure 8 shows how the CFD-DEM coupling technique can capture the tortuous flow through fibre drains. Unlike fluid flowing through non-twisted fibres where flow channels are almost parallel, the fluid travels in a longer path along twisted fibres, resulting in a smaller discharge capacity. The study indicates that coupling CFD with DEM is a promising approach to model hydraulic behaviour of fibrous porous geomaterials.

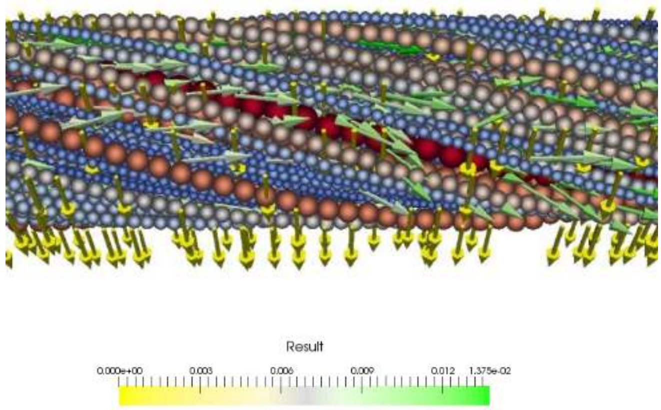


Figure 8: Fluid flowing through fibre drain captured by CFD-DEM coupling

4 BIODEGRADABLE MECHANISM OF NPVDS

A laboratory investigation into the biodegradation of jute drains made from jute and coir was carried out. In this experimental scheme, drains were buried into saturated soft soil obtained from Ballina field (NSW, Australia). Those samples with soil were then maintained in a conditioned room at 22°C and 88% relative humidity. The tensile strength of individual fibres and complete drains was recorded over time (Figure 9). Other properties of soil such as pH and Redox potential which can be used to evaluate the biochemical reactions in soil were also measured periodically.

a) PVJD extracted from soil b) Tension test on single fibres

Figure 9: Laboratory investigation into biodegradation of jute drains

To understand the biological properties of decayed drains, jute samples with soil were sent for genomic (DNA) analysis to identify microorganisms. By this approach, the bacterial profile can be determined. The results showed a large concentration of cellulose degrading bacteria such as species of the families Bacillaceae, Ruminococaceae and Clostridia in decayed jute fibres, particularly near surface soil. Previous biology studies (Leschine, 1995; Goodfellow et al., 2009) show that these bacteria are able to ferment and break cellulose based materials (i.e., jute) into monomers such as glucose. These monomers then serve as foods for other microorganisms such as the sulphate reducing groups (i.e., the Deltaproteobacteria) which are usually predominant in alluvial estuarine soft soils. No lignin degrading bacteria were found in these samples.

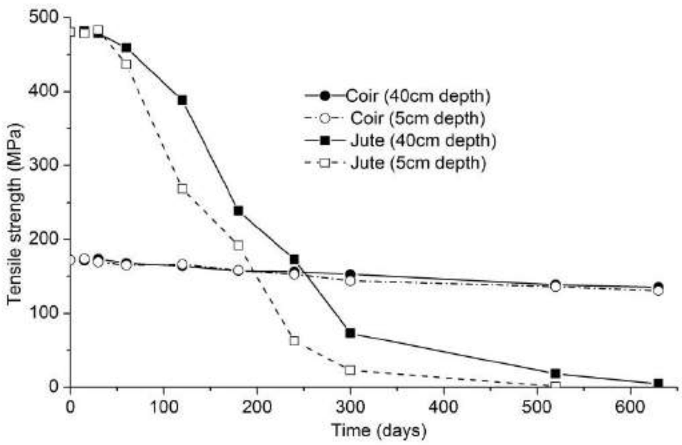


Figure 10: Reduction in tensile strength of jute and coir fibres over time

The degradation in tensile strength of jute fibres subjected to Ballina clay is shown in Figure 10. The tensile strength of jute fibres decreases significantly over time, particularly from 150 to 300 days. The fibres lose approximately 80% its fresh tensile strength after 300 days. The figure also indicates a faster reduction of fibres located on the surface soil (5 cm depth) where there was probably more oxygen available. Unlike jute, coconut shows an outstanding resistance to biodegradation when its tensile strength is almost unchanged over 600 days no matter how deep it was positioned. This was because coir fibres had a large amount of lignin, i.e., approximately 40%.

Figure 11 shows how seriously fibre drains and their jute bundles have degraded over 520 days. The drains become very weak because their jute filters have significantly been decomposed with a large amount of a dark compound generated around. Figure shows the structure of twisted jute bundles has considerably been destructed, which can lead to a reduction in their hydraulic conductivity.

a) Drains extracted from soil after 520 days b) destruction of jute bundles

Figure 11: Observations on degraded drains and their jute bundles

5 INFLUENCE OF BIODEGRADATION ON SOIL CONSOLIDATION

5.1 ANALYTICAL METHOD TO PREDICT SOIL CONSOLIDATION CONSIDERING BIODEGRADATION OF DRAINS

Although many previous studies (Lee et al., 1994; Jang et al., 2001) report a good performance of NPVDs in saturated soft soil, several works (Miura et al., 1995; Kim and Cho, 2009) show a rapid degradation of jute fibre drains in adverse conditions. Particularly jute drain lost almost 80% its tensile strength after only 126 days installed in Ariake clay (Miura et al., 1995). Combined with those observations in the laboratory by the authors (see section 4), an urgent evaluation of how drain biodegradation can affect the consolidation is required.

With respect to the analytical approach for radial consolidation induced by vertical drains (Barron, 1948; Indraratna et al., 2005), the governing equation of excess pore pressure (EPP) can be written as:

$$u + \frac{\gamma_w m_v}{2k_h} \frac{d_e^2}{4} \left(\mu_{n,s} + \mu_q \right) \frac{du}{dt} = 0 \tag{6}$$

where u is the excess pore pressure; d_e is the diameter of the influence zone; k_h is the horizontal permeability coefficient; m_v is the the coefficient of volume compressibility; $\mu_{n,s}$ is a parameter considering the effects of the smear and influence zones, μ_q denotes the reduction in discharge capacity. In this approach, the discharge capacity of drain is assumed to decrease with time due to degradation while other parameters, e.g., the diameter and the length of drain are assumed to be unchanged. The above equation can hence be re-written as:

$$u + f\left(t\right) \frac{du}{dt} = 0 \tag{7}$$

where $f(t)$ is a function including the time-dependent discharge capacity $q_w(t)$. The above is an ordinary differential equation with the following solution:

$$u\left(t\right) = u_o exp\left(-\int_0^t \frac{1}{f\left(t\right)} dt \right) \tag{8}$$

Eq. (8) is the solution describing the dissipation of EPP with respect to a reduced discharge capacity $q_w(t)$. For different degradation function $q_w(t)$, the exact solution will vary accordingly. Details of this mathematical derivation can be found in the publication by Indraratna et al., (2016). For example assuming an exponential reduction in discharge capacity of drains $q_w(t) = q_{wo} \times e^{-\omega t}$ where ω is the decay coefficient, the exact solution for Eq. (8) can be written as:

$$\frac{u(t)}{u_o} = exp\left\{ \frac{-8T_h}{\mu_{n,s}} + \frac{1}{\chi \mu_{n,s} \omega} \left[ln\left(\frac{\mu_{n,s}}{\mu_{qo}} + e^{\omega t} \right) - ln\left(\frac{\mu_{n,s}}{\mu_{qo}} + 1 \right) \right] \right\} \tag{9}$$

where $\chi = d_e^2/(8c_h)$; c_h is the coefficient of consolidation and T_h is the time factor.

An application of Eq. (9) is shown in Figure 12 with assumed soil parameters. An initial discharge capacity 0.43 m^3/day was used in this calculation with respect to the discharge capacity test on jute drains in the laboratory. In comparison with conventional approach, i.e., (Hansbo, 1981) which uses a constant discharge capacity, the proposed method results in a significant retardation in the dissipation of EPP. Particularly, when q_w becomes less than 0.15 m^3/day, the dissipation of EPP by degrading drains begins deviated apparently from the conventional one. The larger the decay coefficient ω, the faster the degradation and the more serious the retardation of EPP.

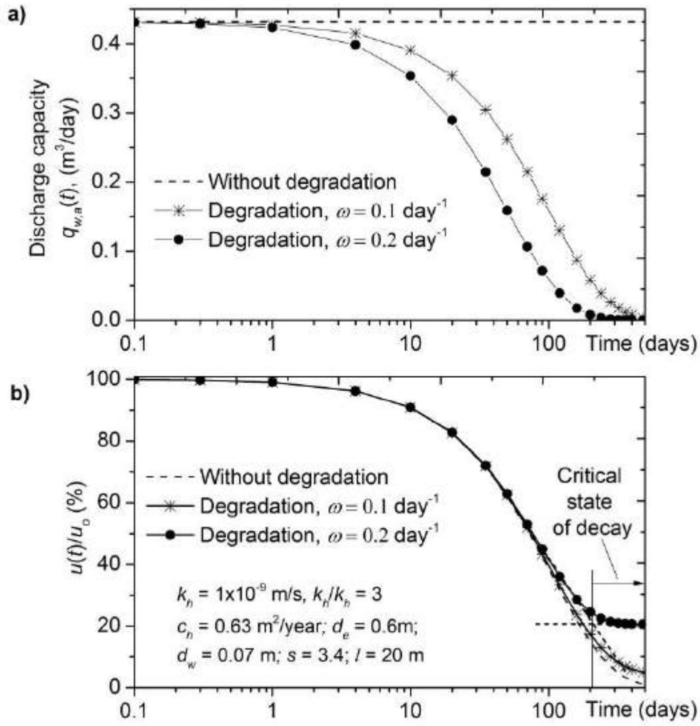


Figure 12: Influence of reduced discharge capacity on soil consolidation: a) exponential reduction in discharge capacity with different rates; b) dissipation of EPP over different rates (modified after Indraratna et al., (2016))

Note that Eq. (8) presents a general solution which can be applied to various degradation forms of discharge capacity. Although only on the exponential reduction is shown in this paper, this approach can work for other degradation forms, e.g., polynomial reductions. Different degradation forms can be incorporated into the dissipation of EPP as follows:

$$u(t) = -\sum_{i=1}^{n} u_{0i} exp \int_{t_{i0}}^{t_{ij}} \frac{1}{f_i(t)} dt \tag{10}$$

where $f_i(t)$ is the function $f(t)$ shown in Eq. (8) corresponding to the time-dependent form $q_{wi}(t)$ in the period $[t_{i0}, t_{ij}]$. Eq. (10) enables a complex reduction which is composed of different forms of discharge capacity to be incorporated into the consolidation behaviour of soil.

5.2 FINITE ELEMENT ANALYSIS CONSIDERING BIODEGRADATION OF DRAINS

Finite Element Method (FEM) has been used extensively to model soil consolidation induced by vertical drains in previous studies. To consider the influence of reduced discharge capacity on the consolidation, a subroutine was created by the authors and incorporated into FEM (ABAQUS, 2012). The subroutine calculates the reduction in the permeability of drain in each time step and update to the FEM for analysing the consolidation process. The major advantage of numerical method over analytical solution is that it is more flexible with any given form of discharge capacity while the analytical method requires a certain form of discharge capacity.

Figure 13 presents the results obtained from the proposed numerical method in comparison with the analytical solution made by the authors (section 5.1). The dissipation of EPP is also significantly retarded by the reduced discharge capacity with approximately 23% residual EPP after 500 days. The results indicate an acceptable agreement between the numerical and analytical methods in considering the influence of drain degradation on soil consolidation. The deviation between the two approaches is found less than 5% for the investigated condition. Note that in this analysis, an exponential degradation with ω = 0.1 day^{-1} was used.

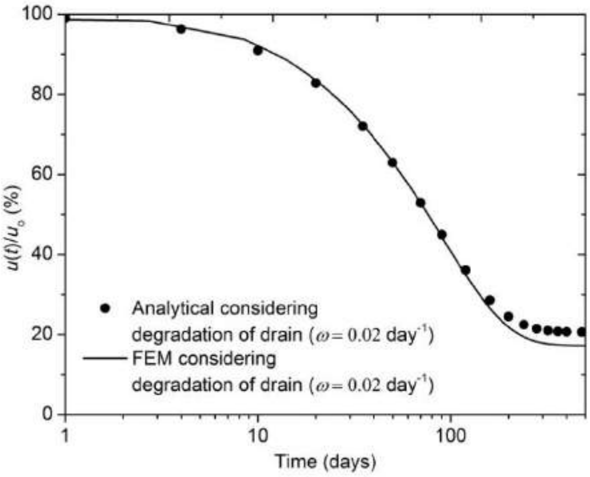


Figure 13: Numerical predictions of soil consolidation induced by degradable drains in comparison to analytical method (modified after Indraratna et al., (2016))

6 CONCLUSIONS

This paper aims to summarise a series of studies addressing existing issues of natural prefabricated vertical drains (NPVDs) carried out by the authors at the University of Wollongong. Although more effort is needed, the following conclusions can be drawn:

a. The drains made from jute and coir fibres have a good discharge capacity (i.e., 0.51 m^3/day at 10 kPa confining pressure). The study found a considerable influence of micro-characteristics such as the size, shape, the uniformity in size and the twisting angle of fibres on the drain hydraulic conductivity. For example the larger the diameter of fibres, the higher the hydraulic conductivity while the more fibres being twisted, the lower the discharge capacity. This understanding plays an important role in improving structure and material designs for NPVDs, enabling the efficiency in their manufacture to be enhanced.
b. A novel numerical approach based on the CFD-DEM coupling was established. DEM with Parallel Bond Model and its modified version proposed by the authors could simulate tensile and bending behaviours of natural fibres such as jute and coir. The results also indicated the numerical method can predict well the micro-hydraulic behaviour of natural fibres, particularly the micro-interaction between fluid and fibres. The conventional Kozeny-Carmen (KC) method showed a certain success in predicting hydraulic conductivity of fibrous media although its accuracy was significantly determined by the empirical constant k_k.
c. Biodegradation of cellulose based fibres, e.g., jute can become very serious when soil contains particular cellulose degrading bacteria such as species of the family Clostridiaceae, Bacillaceae and Ruminococcaceae. Coir resisted very well to biodegradation in saturated soft soil because of its large amount of lignin. The study suggests a need of carrying out an investigation into biological characteristics of soil and incorporating this into consolidation designs.
d. Analytical and numerical solutions which can predict the response of soil consolidation to the drain degradation were proposed by the authors. In these approaches, the reduction in discharge capacity of drains was incorporated into governing equations for soil consolidation. The results indicated the consolidation progress could be retarded considerably (i.e, 23%) as the drain degrades rapidly in adverse media. There was a good agreement between analytical and numerical approaches.

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